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A MIXER-RECEIVER FOR THE PARAMETRIC ACOUSTIC RECEIVING ARRAY

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(U) A receiver for a Parametric Acoustic Receiving Array (PARRAY) based on a high performance mixer appears to be well suited to the requirements of some PARRAY applications. This type of receiver is analyzed and an expression for receiver performance in a PARRAY system is presented. A simple design technique for achieving different frequency response characteristics in the receiver is developed and several examples of the use of this technique are shown.

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I. INTRODUCTION

A receiver for a Parametric Acoustic Receiving Array (PARRAY) based on a high performance mixer offers several potential advantages over the band elimination filter system used in present day designs. First, and perhaps most important for some applications, the mixer-receiver design allows the receiver frequency response to be shaped so that the PARRAY system is less sensitive to high amplitude, low frequency inputs that may be caused by vibration, turbulence, and thermal instabilities in the medium. Second, the mixer-receiver design does not require the high impedance, high Q filters used in the band elimination design. Third, the mixer-receiver allows somewhat greater flexibility in the choice of pump frequency. In the band elimination filter system, the pump frequency is constrained by the crystal filter design to a very narrow range.

The PARRAY mixer-receiver is, in some respects, similar to the phase locked loop which has been used as a demodulator for threshold extension in FM receiver systems.[1] For low modulation frequencies, the PARRAY mixer-receiver acts as a phase locked loop which locks to the incoming phase modulated carrier. However, higher modulation frequencies are not tracked by the loop and so the receiver acts as a linear demodulator for the high frequencies. This difference in response to low and high modulation frequencies is advantageous for some PARRAY applications.[2]

Section II of this report presents an analysis of the mixer-receiver concept and develops relationships between the various adjustable parameters of the receiver and its performance in a PARRAY system. A simple design technique for the receiver based on a particular form of low pass loop filter is developed in section III. Several examples of the system response characteristics obtained by use of the design technique are presented in section IV.

II. RECEIVER PERFORMANCE ANALYSIS

Figure 1 is the functional block diagram of the mixer-receiver. The receiver input signal is the output of the PARRAY hydrophone. The desired output of the receiver is the sum of the carrier sideband signals, appropriately added in phase to maximize response to phase modulation products.

The input signal to the receiver is modeled as

$$s(t) = \cos[\omega_o t + \phi_1(t) + \phi_2(t)] \quad . \tag{1}$$

Here $\phi_2(t)$ is the signal of interest, that is, the signal to which we wish to make the receiver most sensitive, and $\phi_1(t)$ is an interfering signal to which we wish to make the receiver insensitive. For purposes of this development, the frequency band of $\phi_1(t)$ is mutually exclusive of the frequency band of $\phi_2(t)$ and $\phi_1(t)$ occupies a frequency band $\omega<\omega_c$ while $\phi_2(t)$ occupies a band $\omega>\omega_c$ where ω_c is a constant. In the PARRAY, $\phi_2(t)$ is phase modulation due to the nonlinear interaction process, and for virtually all cases of practical interest $\phi_2(t)$ is very small. That is,

$$|\phi_2(t)| \ll 1 \quad , \tag{2}$$

and for this condition s(t) may be adequately represented as

$$s(t) = \cos[\omega_o t + \phi_1(t)] - \phi_2(t) \sin[\omega_o t + \phi_1(t)] \quad . \tag{3}$$

The loop response of the mixer-receiver is described by

$$e(t) = s(t)v(t) \quad , \tag{4}$$

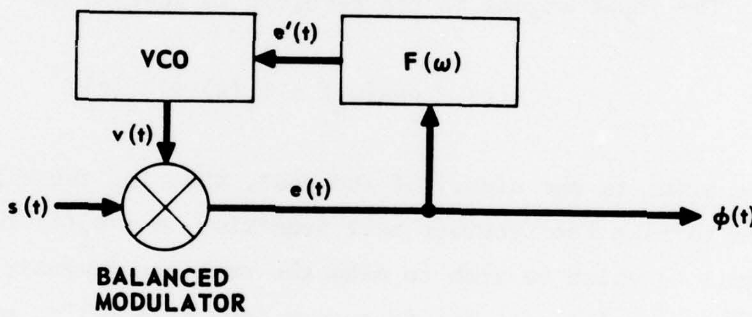

FIGURE 1
PARRAY RECEIVER BLOCK DIAGRAM

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where v(t) is the VCO response defined as

$$v(t) = \sin[\omega_o t + k \int e'(t)dt] \quad . \tag{5}$$

Then, substituting Eqs. (3) and (5) into Eq. (4), and disregarding high frequency terms,

$$e(t) = \frac{1}{2} \sin[k \int e'(t)dt - \phi_1(t)] - \frac{1}{2} \phi_2(t) \cos[k \int e'(t)dt - \phi_1(t)] \quad . \tag{6}$$

If the loop gain is large enough to make the argument of the sine and cosine terms small, these functions may be replaced by their small argument linear approximations to yield

$$e(t) = \frac{1}{2} [k \int e'(t)dt - \phi_1(t)] - \frac{1}{2} \phi_2(t) \quad . \tag{7}$$

This can be readily transformed into the frequency domain as

$$E(\omega) = \frac{1}{2} \left[\frac{k}{j\omega} E'(\omega) - \Phi_1(\omega)\right] - \frac{1}{2} \Phi_2(\omega), \tag{8}$$

where upper case letters denote the Fourier transforms of the corresponding lower case letters.

Referring to the receiver block diagram, it is apparent that

$$E'(\omega) = E(\omega)F(\omega) \quad . \tag{9}$$

Substituting Eq. (9) into Eq. (8) yields the receiver response to the input signal:

$$E(\omega) = \frac{\Phi_1(\omega) + \Phi_2(\omega)}{-2\left(1 + j \frac{kF(\omega)}{2\omega}\right)} \quad . \tag{10}$$

The system transfer function is

$$T(\omega) = \frac{E(\omega)}{\Phi_1(\omega) + \Phi_2(\omega)} = \frac{1}{-2\left(1 + j\,\frac{kF(\omega)}{2\omega}\right)} \quad . \tag{11}$$

Equation (11) defines the receiver frequency response for a given k and $F(\omega)$. At low frequencies and for a low pass form of $F(\omega)$, the transfer function reduces to

$$T(\omega) = \frac{j\omega}{kF(\omega)} \quad , \quad \omega << kF(\omega) \quad . \tag{12}$$

At high frequencies where $\omega >> kF(\omega)$, the transfer function is

$$T(\omega) = -\frac{1}{2} \quad , \quad \omega >> kF(\omega) \quad . \tag{13}$$

That is, the system response is flat at high frequencies with a loss of 6 dB.

For the case $F(\omega)=1$, that is, when there is no filter in the loop, the system transfer function is

$$T(\omega) = \frac{1}{-2\left(1 + j\,\frac{k}{2\omega}\right)} \quad . \tag{14}$$

A plot of this function is shown in Fig. 2. The corner frequency is determined by the loop gain constant k. For all nonzero values of k there is a notch in the system response to low frequencies in the input signal phase modulation. The width of the notch may be controlled by varying the loop gain k. This characteristic may be used to suppress response of the receiver to the low frequency signal $\phi_1(t)$ while passing the higher frequency signal $\phi_2(t)$. This effect may be accentuated by using a frequency selective filter $F(\omega)$ in the loop.

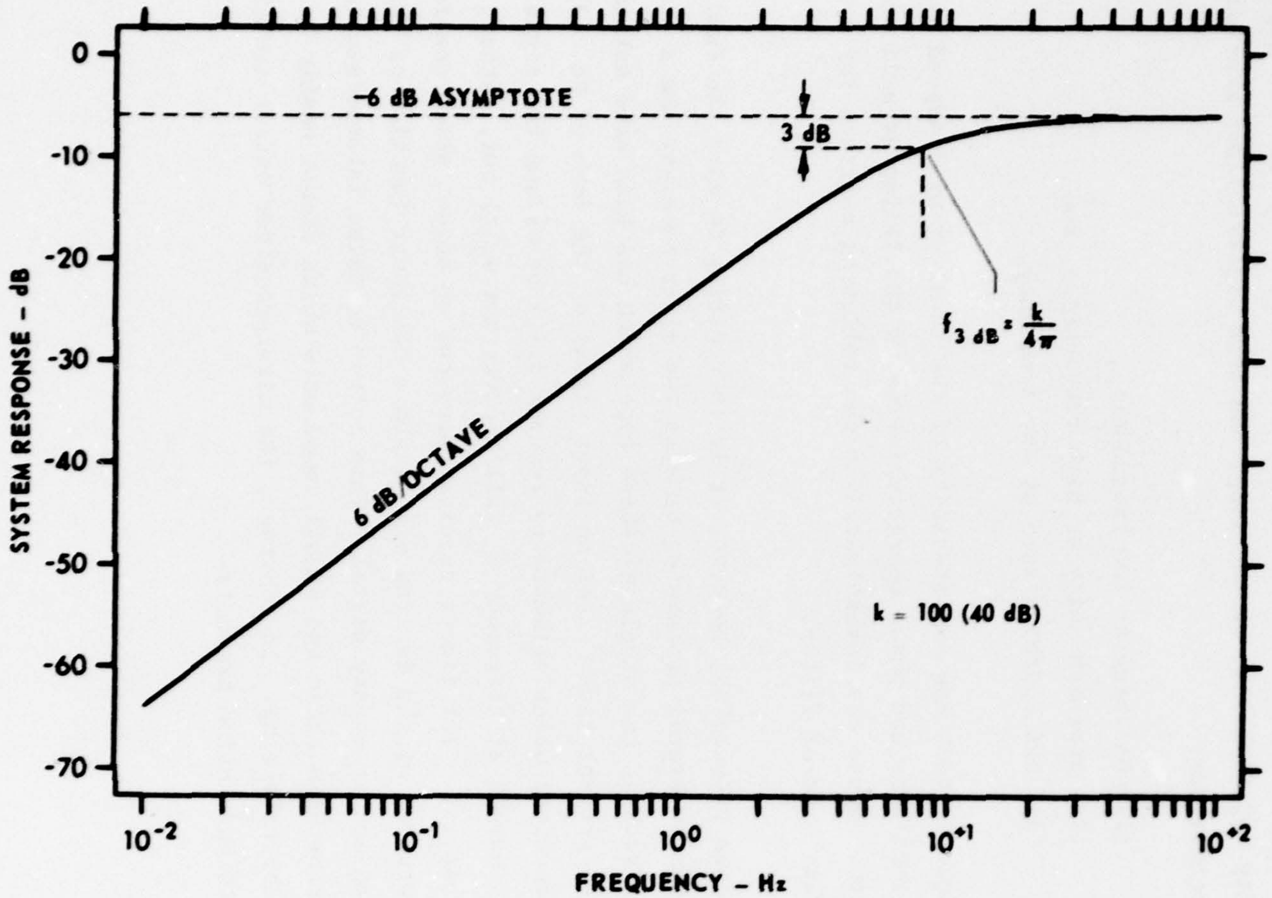

FIGURE 2
RECEIVER RESPONSE FOR NO LOOP FILTER

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The design of the filter $F(\omega)$ presents a significant practical problem in most cases of interest for the PARRAY receiver. To assure linearity and stability of the loop, the term $1+j(kF(\omega)/2\omega)$ must satisfy three conditions:

(1) be large at low frequencies,

(2) approach unity at high frequencies, and

(3) not approach zero at any frequency.

The frequency response and stability of the receiver will depend strongly on the amplitude and phase characteristics of the filter as well as the loop gain. These are investigated in the following sections for a particular type of filter.

Before proceeding, however, it is interesting to note the fundamental difference in signal processing between the mixer-receiver and a linear receiver such as the single sideband type which has been used extensively up to the present time.[3] For an input signal of the form of Eq. (3), a linear receiver which attempts to recover $\phi_2(t)$ by mixing the signal with a pure sinusoid at frequency ω_o will recover not $\phi_2(t)$ but, rather, $\phi_2(t) \cos\phi_1(t)$. The linear receiver produces an output which consists of the product of the desired signal and a nonlinear function of the undesired low frequency signal. This output contains intermodulation products between these two signal components which cannot easily be removed by filtering. In contrast, the mixer-receiver output contains no such intermodulation products.

III. A SIMPLE SYSTEM DESIGN TECHNIQUE

Assume that the loop filter is to be a low pass type constructed by cascading simple resistance-capacitance (RC) low pass sections as shown in Fig. 3. The filter sections are isolated from one another by amplifiers so that the overall filter voltage transfer function is

$$F(\omega) = \frac{1}{\left(1 + j\,\frac{\omega}{\omega_c}\right)^n} \quad , \tag{15}$$

where

n = number of cascaded sections,

and

ω_c = 1/RC, the 3 dB radian frequency of a single section.

Also,

$$|F(\omega)| = \frac{1}{\left[1 + \left(\frac{\omega}{\omega_c}\right)^2\right]^{n/2}} \quad . \tag{16}$$

This filter is to be used in the receiver loop so that the overall receiver transfer function, Eq. (11), has at least α dB attenuation at frequencies below f_1 Hz. Also, the receiver is to have no more than 7 dB attenuation of frequencies above f_2 Hz. The simple design technique to be developed here makes the 3 dB frequency of each section of the filter equal to f_1; however, as will be indicated later, this may not lead to truly optimum results. Then the parameters to be determined in the design process are n and k, the number of filter stages and the loop gain, respectively.

For the low frequency region, the receiver response is given by Eq. (12). For the response to be below α dB in this region,

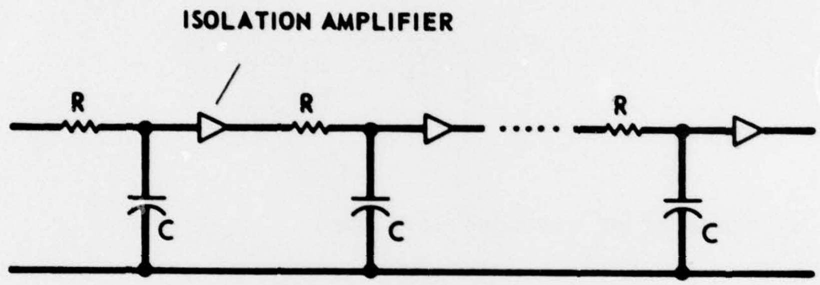

FIGURE 3
LOW PASS FILTER

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$$\left|\frac{kF(\omega)}{\omega}\right| \leqq 10^{\alpha/20} \quad , \quad \frac{\omega}{2\pi} \leqq f_1 \quad . \tag{17}$$

This low frequency specification will always be met if

$$|kF(2\pi f_1)| = 2\pi f_1 10^{\alpha/20} \quad . \tag{18}$$

Now frequency f_1 Hz is also the 3 dB frequency of the filter sections; thus

$$|F(2\pi f_1)| = \frac{1}{2^{n/2}} \quad , \tag{19}$$

and using Eq. (19) in Eq. (18) leads to a specification on the loop gain

$$k = \pi f_1 10^{\alpha/20}\ 2^{(n+2)/2} \quad . \tag{20}$$

This determines the loop gain in terms of the number of filter stages and the specification on low frequency system response.

The high frequency response specification for the system, arbitrarily chosen to be 7 dB, leads to the relationship

$$\left|1 + j\,\frac{kF(\omega)}{2}\right| \leqq 1.12 \quad , \quad \frac{\omega}{2\pi} \geqq f_2 \quad . \tag{21}$$

This specification will always be met if

$$\left|\frac{kF(\omega)}{2\omega}\right| \leqq 0.12 \quad , \quad \frac{\omega}{2\pi} \geqq f_2 \tag{22}$$

or if

$$|kF(2\pi f_2)| = 1.5\ f_2 \quad . \tag{23}$$

This is a very conservative condition and may not need to be satisfied for the overall system response specification to be met; however, it can be used to find a value for n which will always meet the system specification. Then a few smaller values of n can be tried to see whether a simpler filter will suffice.

Substituting Eqs. (16) and (20) into Eq. (23) produces, after some manipulation, an expression for the number of filter stages.

$$n = \frac{\log\left(\frac{f_2}{f_1}\right)^2 - \frac{\alpha}{10} - 1.244}{\log\left[\frac{2}{1 + \left(\frac{f_2}{f_1}\right)^2}\right]} \quad . \tag{24}$$

Actually, n must be an integer and Eq. (24) does not necessarily give an integer result; however, the integer next larger than the value given by Eq. (24) is certain to meet system specifications. In practice, because of the conservative nature of Eq. (23), it is usually found that a somewhat smaller number of filter stages is sufficient.

The design procedure is then the following.

(1) Pick a value of n using Eq. (24) as a guide.
(2) Calculate the loop gain using Eq. (20).
(3) Compute the system response.
(4) Repeat the procedure using successively smaller values of n, recomputing the loop gain each time, to find the smallest n still meeting the desired specifications.

There is no assurance that this leads to an optimal design, but it is useful for predicting the complexity of a receiver needed to meet certain system specifications.

IV. DESIGN EXAMPLES

For example, if a system is to be designed to attenuate frequencies below 10 Hz by at least 30 dB, and frequencies above 30 Hz are to be attenuated by no more than 7 dB, then Eq. (24) predicts that n=5 is sufficient. For this value of n, Eq. (20) yields a loop gain of 81 dB. Actually, a system with only three filter stages and a loop gain of 75 dB is sufficient to meet the specification, as shown in Fig. 4.

As another example, a specification requiring 60 dB attenuation below 40 Hz and no more than 7 dB attenuation above 100 Hz is met by a system having a 9-stage filter and a loop gain equal to 135 dB. The response of this system is shown in Fig. 5. The peak in the response curve in the 90 to 100 Hz region also shows a potential stability problem. This system design could probably be improved considerably by varying the filter cutoff frequency, number of filter stages, and loop gain in a trial and error fashion. Also shown in Fig. 5 are the responses of systems with 8-stage and 10-stage filters. The 8-stage system does not meet the original specifications but is quite stable, while the 10-stage system shows the same tendency toward instability as the 9-stage system.

A third example is that of a system requiring 100 dB rejection of signals below 1 Hz and no more than 7 dB attenuation of signals above 20 Hz. The responses of several systems designed to this specification are shown in Fig. 6. The system with a 3-stage filter meets the specifications with the lowest loop gain; however, this system may have a stability problem. The system with a 4-stage filter may be more desirable even though the loop gain is higher and a more complex filter is required.

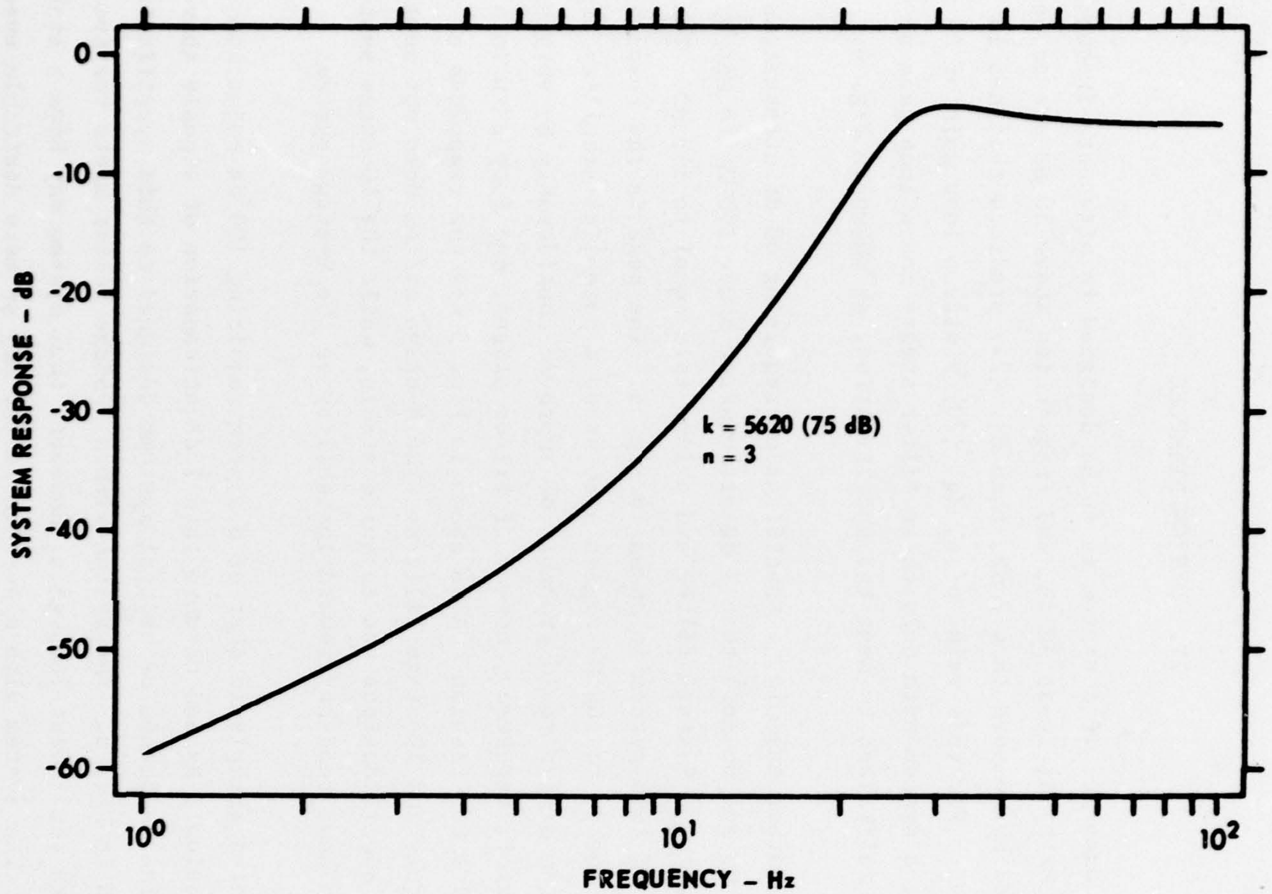

FIGURE 4
RECEIVER RESPONSE FOR 3-STAGE FILTER DESIGN WITH f_1 = 10 Hz

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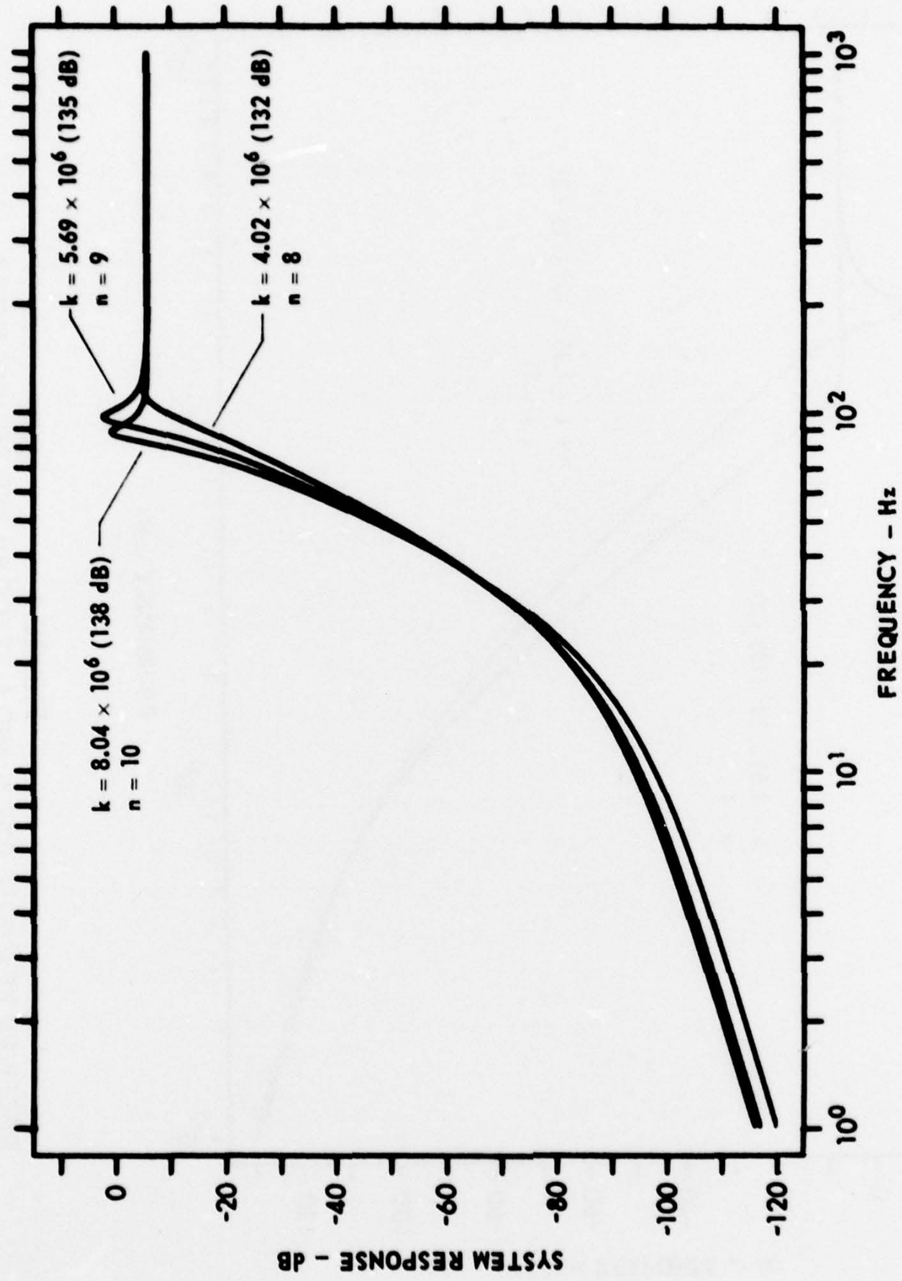

FIGURE 5
RECEIVER RESPONSE FOR 8-, 9-, AND 10-STAGE FILTER DESIGNS WITH f_1 = 40 Hz

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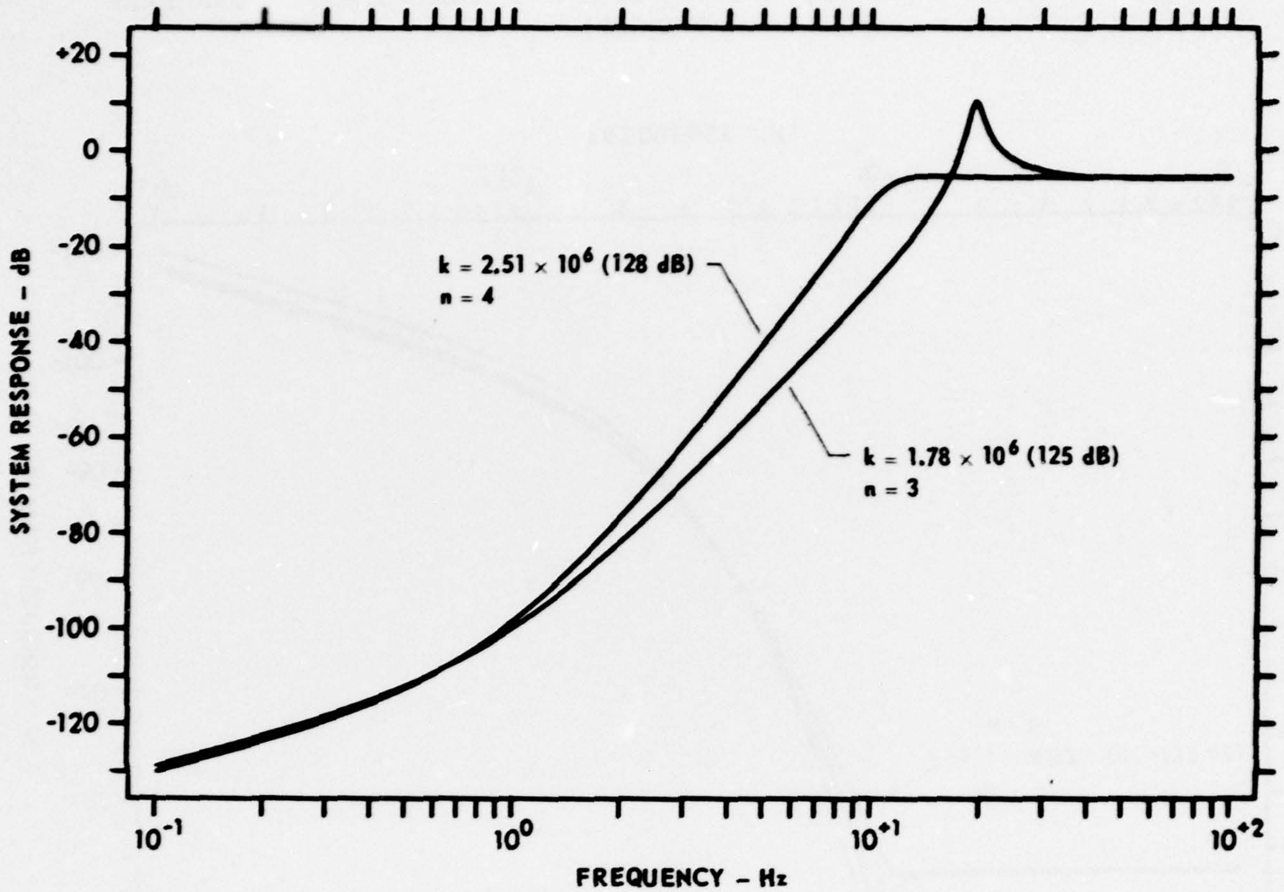

FIGURE 6
RECEIVER RESPONSE FOR 3- AND 4-STAGE FILTER DESIGNS WITH f_1 = 1 Hz

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These examples are not intended to show optimum designs, but rather are intended to give an indication of the range of response characteristics which may be obtained from the system. From these results it appears that the design procedure developed here can provide a good starting point from which better designs can be derived by simple perturbation techniques.

V. CONCLUSIONS

The mixer-receiver concept for the PARRAY has been analyzed and an expression for the performance of the receiver has been developed. A simple design procedure for achieving receiver system response meeting stated performance specifications has been developed and demonstrated in several examples. While the design procedure is based on a particular class of low pass filters used in the receiver, the technique has broad applicability as a means of estimating the performance and design parameters of receivers using other low pass filters.

The results of this investigation indicate that the mixer form of the PARRAY receiver has certain characteristics which may be highly desirable in some PARRAY systems. For applications involving high amplitude, low frequency signal inputs to the PARRAY that might be caused by vibration, turbulence, or thermal instabilities in the medium, the mixer-receiver has particular merit. By proper choice of the design parameters, the mixer-receiver can be made insensitive to low frequency signals and yet retain its sensitivity to high frequency signals. In addition, the mixer-receiver suppresses the intermodulation products between large low frequency signals and small high frequency signals which can be troublesome in systems using purely linear demodulation techniques.

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